

# Hydrology of soils and deep regolith: A nexus between soil geography, ecosystems and land management

Philip J. Schoeneberger\*, Douglas A. Wysocki

*US Department Agriculture-Natural Resources Conservation Service, National Soil Survey Center, NRCS, Lincoln, NE 68508-3866, USA*

## Abstract

Soils and climate control the internal movement of water in and through regolith. This dynamic process, called soil hydrology (also called hydropedology), can be approached within a framework of conceptual models that combine the influences of regional climate (with local variations), stratigraphy (pedo- and geo-stratigraphic circumstances) and topography (macro- and micro-topography). When combined, these elements can provide a practical understanding and prediction of how and where water in the vadose zone will typically move within a landscape. These conceptual models can also be extended to larger land areas, with adjustments made as the elements, such as stratigraphy, vary. In situations where highly detailed monitoring is not cost-effective, soil hydrology provides a means of incorporating what is known about water flow into our understanding, presentation and use of the soilscape. Soil hydrology can, in turn, be used to explain soil features (soil morphology), distributions (soil geography) and ecosystem functions (dynamics). It can also be used to guide land management decisions by providing a basis for partitioning the landscape into subsets with different input tolerances.

© 2004 Published by Elsevier B.V.

**Keywords:** Soil hydrology; Regolith; Hydrogeology; Deep soils; Water movement

## 1. Introduction

Water functions both as a catalyst for pedogenic processes within soil and as a vehicle for the transport and redistribution of materials and energy within and between soils. Soil hydrology, the study of water movement within soils and through landscapes, represents a nexus that bridges the diverse disciplines

of pedology, hydrology, geology and ecosystems analysis. Soil hydrology can substantially explain soil morphology, soil geography and ecosystem function (e.g., fluxes of soluble constituents: distributions and direction of movement). Soil hydrology can also serve as a tool for selecting optimal land use decisions for specific applications and tailored to different parts of landscapes, such as vadose zone issues regarding contaminant movement above and to the groundwater table. Lastly, soil hydrology commonly involves more than just the uppermost 2 m emphasized in soil taxonomy and soil inventory. Vadose zone water movement is affected not only by the availability of

\* Corresponding author. Tel.: +1 402 437 4154; fax: +1 402 437 5336.

E-mail address: [philip.schoeneberger@usda.gov](mailto:philip.schoeneberger@usda.gov)  
(P.J. Schoeneberger).

water (inputs minus the outputs), but also by the thickness of porous media available to hold and internally transport water. Unless an aquiclude or permanent groundwater table occurs near the land surface, the vadose zone will commonly exceed the uppermost 2 m. Consequently, such deep regolith must be encompassed in models and analyses if it affects vadose zone dynamics.

### 1.1. Recent progress

Considerable advances have been made in recent years in extending the hydrologic cycle to an understanding and articulation of soil hydrology (Fig. 1). This has evolved in two related but different contexts: (a) theoretical/mathematical modeling approach, generally focused on laboratory or limited point data (pedon, field-level experiments; Parlange and Hopmans, 1999), and (b) in situ (field) measurement and landscape assessment (Wakeley et al., 1996). Both contexts recognize the need to understand both the specific details of how and why water moves in porous media, as well as how to project these processes to large land areas. The emphasis here is upon the second context of determining and exploiting field and landscape-scaled conceptual models and subsequent inferences of water movement through landscapes (Fig. 2).

Some of the most substantive advances in soil hydrology regarding the landscape context have come from wetland soil studies (e.g., Richardson and

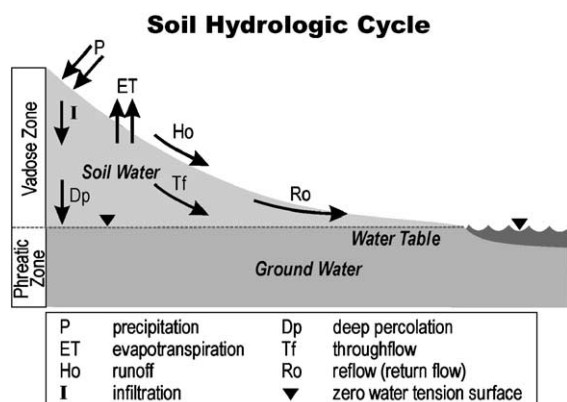


Fig. 1. The soil hydrologic cycle-water movement through regolith (adapted from Richardson, 1993; Wysocki and Schoeneberger, 2000).

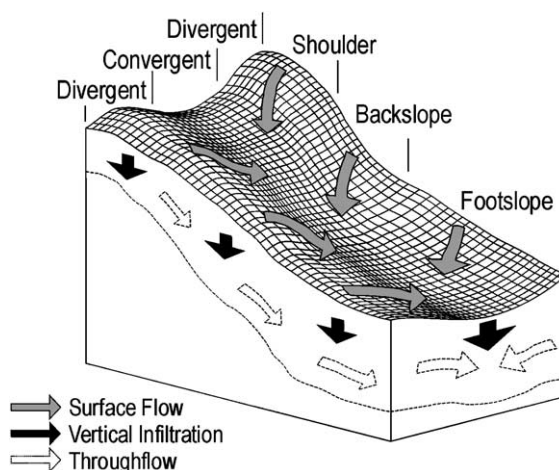


Fig. 2. An example of a soil hydrology conceptual model: differential water flow over and within a hilly landscape as influenced by topography and slope shape (after Pennock et al., 1987).

Vepraskas, 2001). These advances have resulted in gestalt shifts in scientific thinking by facilitating:

- (1) A shift from qualitative to more quantitative, field-scale monitoring and assessment of soil hydrologic parameters and hydromorphic features (e.g., saturation, soil redoximorphic phenomena) and dynamics (e.g., timing, duration and direction) (Clausnitzer et al., 2003; D'Amore et al., 2000; Jenkinson et al., 2002; Karathanasis et al., 2003; Rabenhorst et al., 1998; Thompson and Bell, 1998).
- (2) Elaboration on the nature of, linkages between, and implications of soil hydrosequences (caten-like soilscape sequences from the best drained to the least drained soils in a system). For example, while addressing wet soils, the pioneering Wet Soils Monitoring Program (Hudnall et al., 1990; Wakeley et al., 1996) promoted monitoring entire soil hydrosequences ('best-to-least' drained monitoring), rather than focusing on wet soils alone, disconnected from the surrounding landscape. Further, imbedded within the programmatic criteria for identifying hydric soils, hydrogeomorphic models (HGMs) have been developed which attempt to integrate vadose zone hydrology with geomorphology (Brinson, 1993; Richardson and Brinson, 2001).

This recent progress has provided corroboration of vadose zone dynamics, particularly with the soil zone, and provides a scientific base from which to extend more cost-effective, conceptual models to broader landscapes.

### 1.2. Soil morphology and soil geography

Many soil features are directly related to presence or absence of anaerobic reducing conditions for extended periods, commonly associated with saturation. The most common and visually intuitive link of soil hydrology to morphology is the presence and location of secondary concentrations or depletions within soil profiles (e.g., redoximorphic features associated with macropores or internal matrix conditions; Schoeneberger et al., 2002). Soil water dynamics (and by extension, soil hydrology) has been historically used to explain major morphological features such as perched water tables or the prevailing depth of leaching (Fig. 3). It can also be used to explain major secondary mineral distributions within soils: calcium carbonate, gypsum, manganese and iron oxide concentrations or reductions, and soil color patterns in general.

Soil classification and geography emphasized a presence/absence attitude to soil morphology for most of the 21st century. A major advance in recent years has been an informal movement to extend the traditional emphasis of soil morphology of a point (e.g., a pedon) and reconnect it to the landscape surrounding it. This has begun to move us beyond a “static” treatment of catenas by infusing the dynamic aspect of water flowing laterally through soil (hydrosequences). Pedon morphology can be placed within a three-dimensional context that explains differential concentrations across a landscape (Park and Burt, 1999; Steinwand and Richardson, 1989; Wysocki and Schoeneberger, 2000). For example, the association of increased manganese concentrations with wetter portions of a hilly landscape (e.g., McDaniel and Buol, 1991; McDaniel et al., 1992) is an example of migration and concentration of specific soil constituents facilitated by lateral internal water movement. Definitive, widespread, soil geography patterns closely associated with soil hydrology dynamics include the “red-edge effect” of the Atlantic Coastal Plain (Daniels and Gamble, 1967). The dominant soil matrix colors brighten in color value and chroma as one moves away from the flat (wet) interior of low,

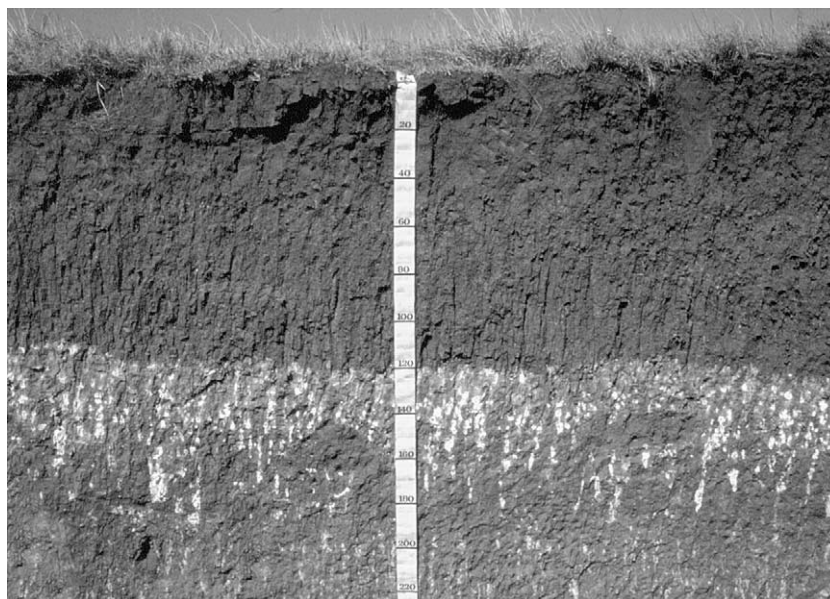


Fig. 3. Prevailing depth of leaching, marked by concentrations of translocated calcium carbonates in a semi-arid, upland mollisol of western Oklahoma, USA (scale is in centimeters).

broad interfluvial and approaches the drier edge of drainageways (Fig. 4). Another widespread soil geographic pattern associated with internal water flow dynamics is the “wetland-edge effect” of the Prairie Pothole region (Steinwand and Richardson, 1989; Richardson and Vepraskas, 2001). This soil pattern is characterized by laterally translocated, secondary minerals (carbonates and gypsum) that concentrate in the soil matrix and form crude ‘bath-tub ring’ soil patterns around the perimeter of wetlands.

### 1.3. Ecosystem function and fluxes

By combining point data (e.g., pedon morphology) with soil geography (e.g., relationships of adjoining soil bodies, available in soil map units), soil hydrology can be used to explain and to predict lateral redistribution of water and associated materials within soils and through landscapes. The prevailing direction of water flow, its relative magnitude and the composition of the soil matrix through which the water moves establish the dominant soil/solution chemistry. This in-turn impacts the materials that will be concentrated and what will be transported elsewhere. For example, differences in the retention/transport rate of various solutes moving through soil and saprolite where compared in a study of various pollutants representative of wastewater

disposal systems (Amoozegar and Hoover, 1989). Results showed differences in the rate of movement and degree of retention between anions, non-reacting solutes and cations reflective of the type of soil and saprolite through which the materials passed. In natural settings (ecosystems), the movement or retention of soil water and materials which it carries establishes the specific growth environment (e.g., presence/absence of gypsum and other salts) for vegetation and subsequent biotic assemblages (flora and fauna).

In this paper, we discuss various factors that substantially affect soil hydrology. Typically, these factors can be readily assessed and then combined to realistically explain/predict the general water movement through soils and landscapes and to predict and/or explain the subsequent soil patterns and pedon morphology. Our premise is that soil hydrology can be used to:

- (1) Explain the occurrence of many soil features (soil morphology) and recurring soil patterns (soil geography);
- (2) Help explain ecosystem function (fluxes and general direction of soil processes and associated materials); and
- (3) Guide the selection of landscape-based management decisions.

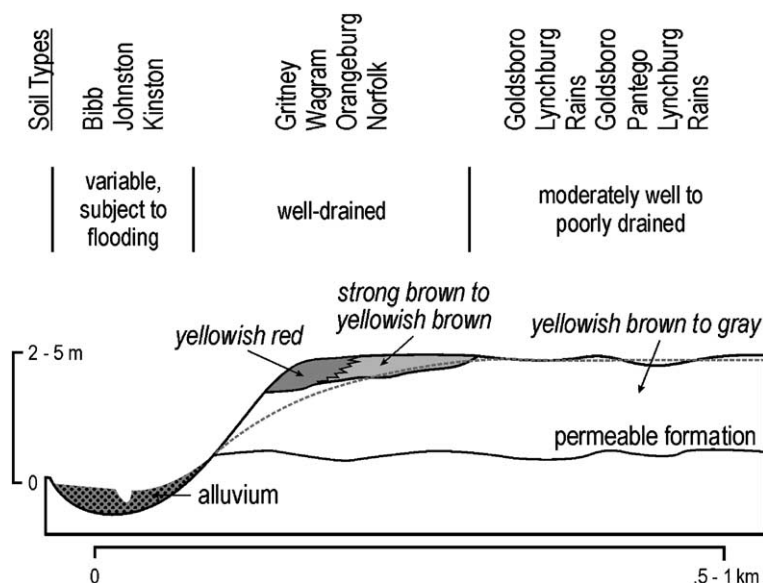


Fig. 4. The “red-edge” effect—a soil hydrosequence in Washington County, NC, USA.

## 2. Discussion

### 2.1. Climatic phenomena

Climate controls the hydrologic circumstances of an area by determining the magnitude and timing of precipitation inputs, and influencing evapotranspiration losses. Climate needs to be addressed at several scales and over several time frames.

#### 2.1.1. Regional climatic control

The prevailing regional climate determines recharge and discharge sites within landscapes (Heath, 1982, 1984, 1987; Richardson and Vepraskas, 2001; Rosenshein, 1988), and controls the dynamics between these sites by determining the general water flow patterns of the vadose zone. For example, in much of the continental United States, this takes the simplistic form of three general climatic zones: (1) humid, (2) sub-humid/semi-arid, which are well established in geo-hydrology (Rosenshein, 1988; Winter and Woo, 1990), and (3) an intervening transition zone of variable climate. The humid zone is equivalent to the “gaining streams” context where precipitation inputs exceed evapotranspiration outputs, resulting in a net excess of internal water available for drainage and resulting in groundwater tables that loosely mimic surface topography. The excess water moves through the landscape from topographic highs towards and discharges in topographic lows such as streams or other water bodies (Fig. 5a). The opposite analogue (semi-arid/arid climate) is essentially the “losing streams” context of geohydrology where precipitation inputs are less than evapotranspiration outputs, resulting in a net deficit of internal water. In this environment, the groundwater table is loosely an inversion of the surface topography. This system responds by moving subsurface water through the landscape away from water bodies (e.g., streams) and recharge depressions with hydraulic gradients moving towards adjacent higher ground (Fig. 5b). Occurring between these two climatic settings is a gradational transition that fluctuates between the humid and semi-arid condition (i.e., annual precipitation inputs can be either > or < evapotranspiration losses). This climatic tension zone is controlled by the relative wetness or dryness of a given year, decade, etc. Wet conditions (large precipitation events, or multi-year wet cycles)

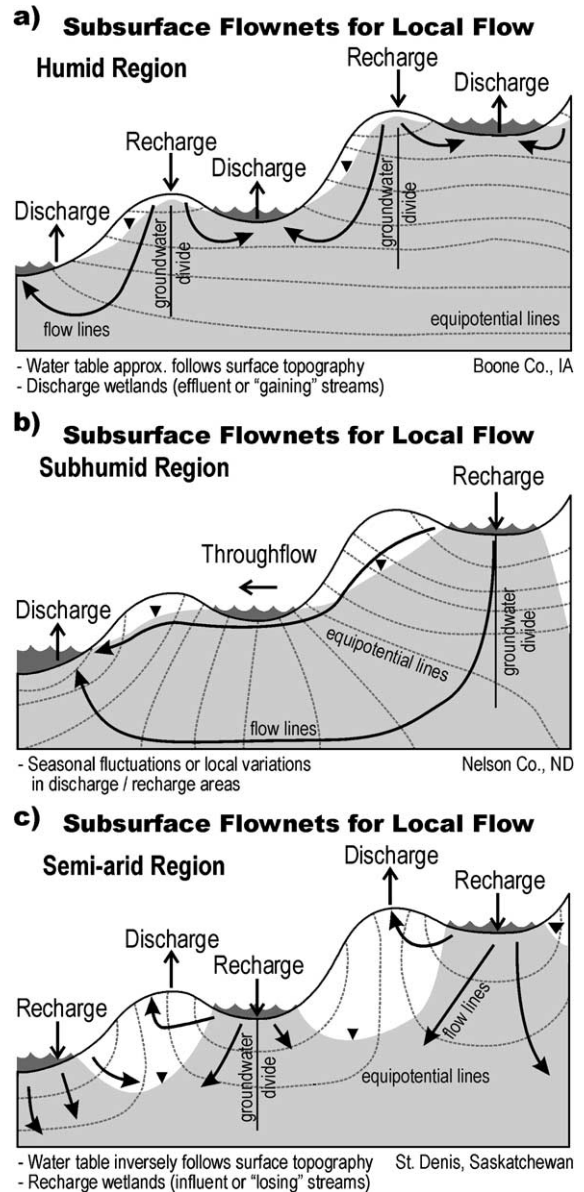


Fig. 5. Representative subsurface flownets (equipotential lines and associated water-flow lines) in (a) humid, (b) sub-humid and (c) semi-Arid environments.

drive the system to hydrologically behave as a humid environment, whereas prevailing dry conditions (e.g., droughts) drive the system to behave as semi-arid environments (Fig. 5c).

Understanding dominant regional climatic dynamics allows one to predict the general patterns

(direction) of water movement in the vadose zone. A modest extension of this understanding can provide an estimate of the soil hydrologic consequences of stochastic shifts in climate (e.g., wet or dry cycles). It also enables one to decipher the climate record imprinted into soil morphology of an area. For example, reconstructing paleoclimate of the Pleistocene commonly involves deciphering and separating the soil morphology record of current conditions from that of paleo-conditions (e.g., relict morphology; [Gile and Ahrens, 1994](#); [Gile et al., 1981, 2003](#)).

Obviously, localized climatic variations can supercede or modify the regional climatic dynamics and must be accommodated. One example is orographic effects (e.g., wet, windward slopes and drier, leeward rain shadows are common in mountain ranges that experience prevailing wind patterns). Similarly, proximity to large water bodies can cause precipitation patterns that predictably deviate from the dominant regional climate (e.g., “lake-edge effects”—the milder temperatures and increased precipitation adjacent to the Great Lakes of North America; [Soil Conservation Service, 1981](#)). Localized climatic deviations should be integrated into a conceptual climatic model and extended/applied aurally.

#### *2.1.2. Stochastic climatic variations (temporal changes)*

The prevailing regional climate alone is insufficient to address climatic influence on soil hydrology; it merely sets the stage. Other, more transient climatic circumstances are common, confounding and important to how water moves through landscapes. Such phenomena that can be evaluated for a given area must also be addressed. For example:

*Perennial variability:* precipitation levels vary between individual years as well as between longer blocks of time (e.g., decades): Detailed climatic records make it possible to refine or qualify assumptions about regional climate patterns. They also make it possible to explore deviations from the norm. Irregular but recurrent wet or dry episodes, such as El Nino-related cycles ([Rosenzweig, 2001](#)), may temporarily shift the prevailing climate patterns in predictable ways for a period of time, before reverting to an historical norm. Such deviations from regional assumptions can be

accommodated by an “If, then ...” approach to climate portions of hydrologic models.

*Seasonal variability:* variations in precipitation within years, where relevant, also needs to be recognized. Recurrent precipitation patterns associated with seasonal variations should be addressed (e.g., Mediterranean vs. continental vs. monsoon climatic patterns). Depending upon the specific issues of concern, seasonal climate variation can be crucial (e.g., timing of cropping cycles or fertilizer applications).

#### *2.1.3. Soil temperature and moisture (frozen ground)*

Other climate-related conditions can have major influence on water movement through landscapes. For example:

*Permafrost* (permanent) functionally behaves as a quasi-permanent impermeable layer to subsurface (downward) water movement year-round ([Emerson, 1991](#); [Kimble and Ahrens, 1994](#)). This condition is limited primarily to high northern latitudes and the Polar regions but is regionally extensive. *Seasonally frozen ground* can function as an ephemeral, impermeable layer for only part of the year and still be important ([Iskandar et al., 1997](#)). Soil erosion events on croplands can be highest when rain occurs on partially thawed ground ([Fig. 6](#); [Dingman, 1975](#)). Seasonally frozen ground (ephemeral frost) is a common, recurring condition in temperate latitudes and higher elevations, such as in the continental USA and southern Canada ([Iskandar et al., 1997](#)).

### *2.2. Stratigraphic phenomena*

The stratigraphy of regolith materials strongly influences soil hydrology by enabling, deflecting or preventing internal water movement.

#### *2.2.1. Geo-stratigraphic factors (sediments and bedrock)*

Several common attributes of the regolith or bedrock have direct impact on the direction and magnitude of internal water movement:

*Stratigraphy*—the composition, porosity, thickness, orientation, sequencing and lateral continuity of



Fig. 6. Water emerging from a rodent burrow as reflow and eroding a rill in the upper 10 cm (thawed portion) and flowing across the top of the still-frozen lower portion of a plow layer in a harvested wheat field; Willamette Valley, OR.

regolith strata can dictate the magnitude and direction of internal water flow (e.g., D'Amore et al., 2000; Jenkinson et al., 2002). A porous material (e.g., sand) can inherently move more water vertically (Hillel, 1982) and laterally (Shaw et al., 2001) than non-structured clay. However, a porous sand layer with an intrinsically high conductivity, but confined by non-porous sediment, may be unable to move water laterally (e.g., a “clay pot” effect).

**Dip**—the attitude (“dip”) of non-horizontal strata can deflect internal water movement down-dip (e.g., the more impermeable and laterally continuous the strata, the more effective the deflection of subsurface water). Where the dip is known, adjustments to water flow models within the vadose zone can be included (Driese et al., 2001). **Topography**—local relief affects subsurface water flow in muted but potentially similar ways to how

it affects surface runoff. Surface topography establishes areas of convergent and divergent water-flow that in turn determine localized areas of higher or lower infiltration (Fig. 2). Macro-topography, topography expressed at the scale of landforms or landscapes, combines with regional climatic controls, to determine the general direction of subsurface water flow. In soils, this is commonly reflected by the distribution of soil drainage classes across a landscape. In some settings, such as hilly terrain in humid climates (Fig. 7a), the best drained soils occur on the highest elevations. In other settings, such as broad interfluvies of nearly level coastal plains, the highest elevation can have the most poorly drained soils, with better drainage at lower elevations near drainage margins (Figs. 4 and 7b).

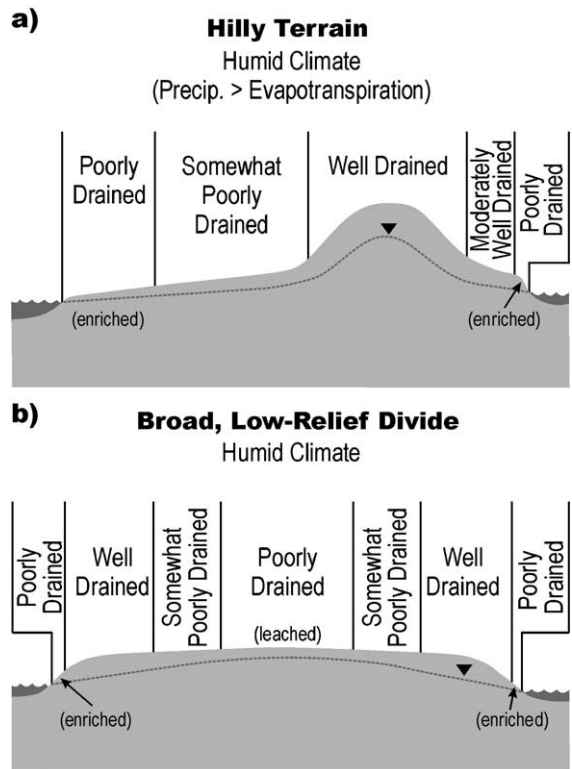


Fig. 7. Generalized soil drainage distribution across landscapes in humid environments as affected by landscape position (modified from Buol et al., 1997): (a) hilly terrain, (b) low-gradient setting with a nominal drainage network (e.g., a broad interstream divide on a low-relief coastal plain).

### 2.2.2. Pedo-stratigraphic factors (horizon differences)

A variety of soil properties also directly affect internal water movement, and hence are relevant to soil hydrology models. These properties or attributes commonly occur within soils and may vary between soil horizons:

*Soil texture*—the particle size, composition and textural changes with depth (e.g., sandy vs. clayey soil) associated with pedogenic development such as argillic horizons can enhance, diminish or deflect internal water flow (e.g., D'Amore et al., 2000; Jenkinson et al., 2002; Shaw et al., 2001; Wilson et al., 1990).

*Clay mineralogy*—the amount and types (e.g., kaolinite vs. smectite) of clay directly affect water flow via porosity and soil structure, as well as influencing the significance of seasonal changes in soil physical properties (e.g., shrink/swell cycles associated with wetting and drying).

*Meso/macropore networks*—interconnected pores in soil layers, or the lack thereof (e.g., soil structure, faunal burrows such as earthworms, termites; Mando et al., 1996), and voids derived from plant roots have a substantial impact on both vertical and lateral water movement (Soil Survey Staff, 1993). For example, a well-structured soil such as the Cecil soil type may readily conduct water internally despite very high clay percentages (Schoeneberger et al., 1995). In localized areas, faunal activity of large animals can dominate soil hydrology dynamics, as with the impact of pedoturbation by beaver (e.g., Johnston, 2001) or extensive rodent burrows such as kangaroo rats in the arid southwestern US.

*Vegetative consumption*—the evapotranspirative extraction of soil water by plant communities can be substantial and can dramatically alter local water flow patterns; examples include wetland fringes (Richardson and Vepraskas, 2001), riparian buffer strips (Lowrance et al., 1997) or as forests (Jenkinson et al., 2002).

*Microtopography*—as with macrotopography, small scale differences in land surface can substantially redirect internal local water flow patterns, both in general and following seasonal precipitation trends (e.g., Hopkins, 1997).

These and other pertinent soil parameters can be incorporated into soil hydrology models to refine where water is prone to move within landscapes. Such information can be used overtly in a specific conceptual model if the effect is pervasive, or used as “qualifiers” to convey recurring variations within a particular model and setting for more localized but predictable recurrence.

### 2.3. Management decisions

The combination of soil hydrology and geomorphology provides a potent and practical way to partition the continuum of landscapes into management subsets that are environmentally relevant to land

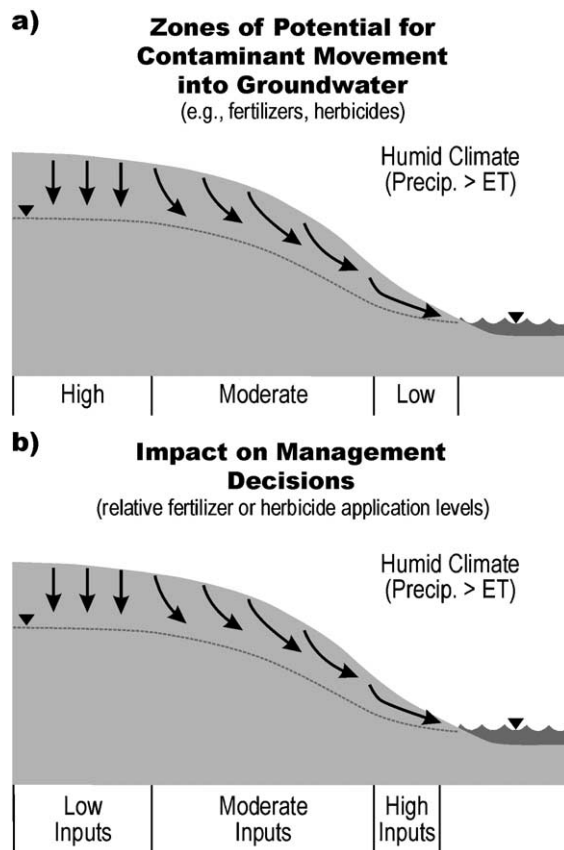


Fig. 8. (a) Zones of relative potential for contaminant movement through regolith and into groundwater from various hillslope positions in a semi-arid climate. (b) Example of subsequent differences in land management choices regarding fertilizer input levels.

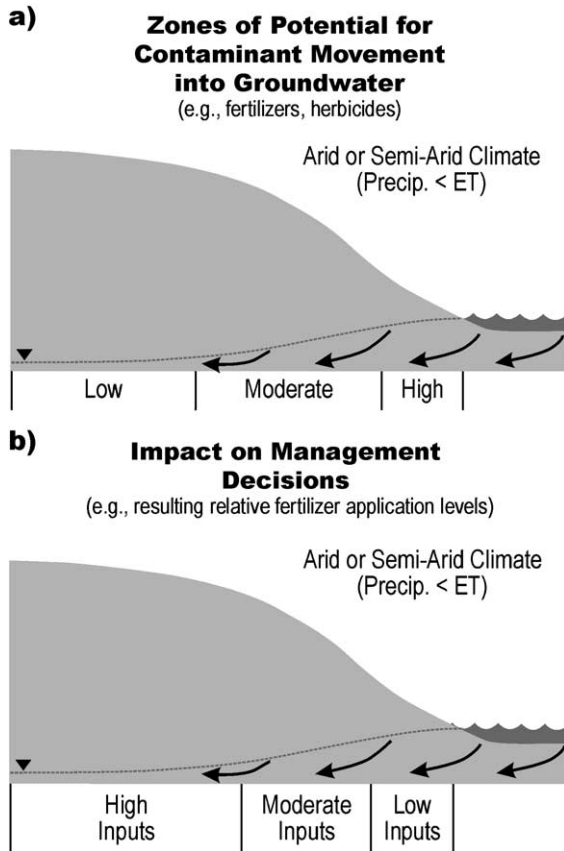


Fig. 9. (a) Zones of relative potential for contaminant movement through regolith and into groundwater from various hillslope positions in a humid climate. (b) Example of subsequent differences in land management choices regarding fertilizer input levels.

management choices. Soil hydrology models can be readily combined with soil geomorphology information contained within soil and other natural resource inventory databases, and/or with digital elevation models (Bell et al., 1992; Thompson and Bell, 1998; Thompson et al., 2001) to identify and then array discrete portions of the landscape (e.g., similar slope shape, topographic position, etc.). Soil properties such as ion exchange capacities can be merged with soil hydrology models to assess not only where the water is likely to go, but what will happen to materials through which it passes (e.g., what materials (cations vs. anions) and relatively how much will be retained, vs. what will migrate). Subsequently, predictions can be made regarding how different segments of landscapes are apt to respond to particular land treatments.

Environmentally sensitive areas can be identified and distinguished from less sensitive areas on broad (e.g., watershed; Lowrance et al., 1997) and localized (e.g., “within field”) levels. Once identified, these areas of different sensitivity can be incorporated into land management options (e.g., watershed planning, amendment application rates).

For example, if one knows that a given area is controlled by a prevailing semi-arid climate, water can generally be expected to flow away from water bodies through the bounding regolith and towards upland areas (Fig. 5). Combined with topographic (e.g., local relief) and geomorphic (e.g., hillslope position) information, a landscape can be partitioned into discrete pieces that have comparatively different

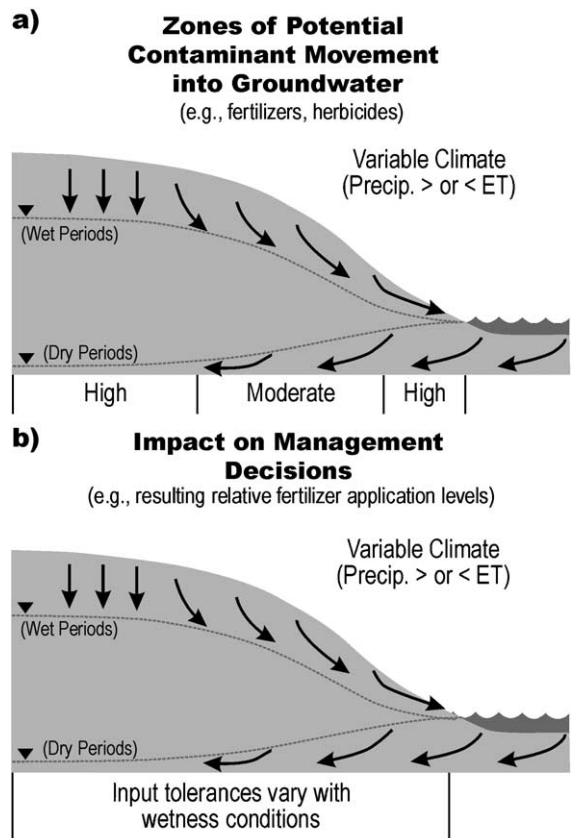


Fig. 10. (a) Zones of relative potential for contaminant movement through regolith and into groundwater from various hillslope positions in a variable (transition) climate. (b) Subsequent differences in land management choices regarding fertilizer input levels will vary along with the climate cycle.

potentials to retain or transport chemical inputs (Fig. 8). This approach is applicable to localized issues, such as providing a scheme for partitioning fields for variable application rates of herbicides, fertilizers, etc., in precision farming. When evaluated with the influence of regional climate patterns, various scenarios become apparent (Figs. 9 and 10). This method is also applicable to much larger scales, wherein differences in physiography and regolith/bedrock lithology can be segregated. Such an approach was used to identify and articulate different regolith circumstances across the Chesapeake Bay watershed and then evaluate the likely response to phosphorus and nitrogen inputs across the watershed and subsequent land management options (Lowrance et al., 1997).

### 3. Conclusions

Regional climate determines the dominant water discharge/recharge sites in a landscape and establishes the dynamics (fluxes) between them. These dynamics largely drive vadose zone water-flow patterns. Vadose zone water flow patterns are modified by pedo- and geo-stratigraphic variations and continuity, and by vegetative consumption. Soil hydrologic relationships can be identified and geomorphically and physiographically tailored (specified) to capture differences within and between land areas.

Conceptual soil hydrologic models are a viable way to explain and predict soil morphology, soil geography and the prevailing direction of water movement through landscapes. They can be readily developed for many areas largely from available information. These models must consider, and are relevant to, soil and other regolith above the groundwater table. They can be robust, pragmatic and extremely useful for explaining the morphology found within soil pedons (soil inventory), explaining and predicting soil patterns (soil geography). They can also serve as a means for choosing the most efficacious land management options and their optimal distribution from amongst potential strategies in order to optimize productivity while protecting natural resources and the environment. Such conceptual models can provide a framework within which to assign realistic ranges or norms for rates of movement and retention of specific materials. However, con-

ceptual models do not typically include explicit, quantitative data for every possible circumstance, and therefore are not a substitute for intensive monitoring required in some circumstances (e.g., toxic waste sites). Nonetheless, this approach does provide considerable predictive value of dominant water flow dynamics within landscapes, applies to larger areas than site-specific models, and does not require the costs and time intrinsic to intensive, site-specific monitoring.

Lastly, soil scientists are uniquely placed within the earth sciences to utilize the soil hydrology approach because of their training and regular activities that require intimate knowledge and daily integration of soil, regolith, hydrologic, vegetative and climatic information.

### References

- Amoozegar, A., Hoover, M.T. 1989. Movement of water and chemical pollutants from wastewater disposal systems through the soil and saprolite of Piedmont landscapes (UNC-WRRI-89-249). Water Resources Research Institute, University of North Carolina, North Carolina State University, Raleigh, NC.
- Bell, J.C., Cunningham, R.L., Havens, M.W., 1992. Calibration and validation of a soil-landscape model for predicting soil drainage classes. *Soil Sci. Soc. Am. J.* 56, 1860–1866.
- Brinson, M.M., 1993. A hydrogeomorphic classification for wetlands. Wetlands Research Program Technical Report WRP-DE-4, US Army Corp Engineers, Washington, DC.
- Buol, S.W., Hole, F.D., McCracken, R.J., Southard, R.J., 1997. *Soil Genesis and Classification*, 4th ed. Iowa State University Press, Ames, IA.
- Clausnitzer, D., Huddleston, J.H., Horn, E., Keller, M., Leet, C., 2003. Hydric soils in a southeastern Oregon vernal pool. *Soil Sci. Soc. Am. J.* 67, 951–960.
- D'Amore, D.V., Stewart, S.R., Huddleston, J.H., Glasmann, J.R., 2000. Stratigraphy and hydrology of the Jackson-Frazier Wetland, Oregon. *Soil Sci. Soc. Am. J.* 64, 1535–1543.
- Daniels, R.B., Gamble, E.E., 1967. The edge effect in some ultisols of the North Carolina coastal plain. *Geoderma* 1, 117–124.
- Dingman, S.L. 1975. Hydrologic effects of frozen ground: literature and synthesis. US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Special Report 218.
- Driese, S.G., McKay, L.D., Penfield, C.P., 2001. Lithologic and pedogenic influences on porosity distribution and groundwater flow in fractured sedimentary saprolite: an application of environmental sedimentology. *J. Sediment. Res.* 71, 843–857.
- Emerson, D.G., 1991. Documentation of a heat and water transfer model for seasonally frozen soils with application to a precipitation-runoff model. US Geological Survey, USGS Open-File Report 91-462, Denver, CO.

- Gile, L.H., Ahrens, R.J. (Eds.), 1994. Supplement to the Desert Project Soil Monograph: Soils and Landscapes of a Desert Region Astride the Rio Grande Valley Near Las Cruces, New Mexico. USDA-Soil Conservation Service, Soil Survey Investigations Report No. 44, vol. 1: Soil water and soils at the soil water sites, Jornada Experiment Range. National Soil Survey Center, Lincoln, NE.
- Gile, L.H., Hawley, J.W., Grossman, R.B., 1981. Soils and geomorphology in the basin and range area of southern New Mexico—guidebook to the Desert Project. Memoir 39. New Mexico Bureau of Mines & Mineral Resources, Socorro, NM.
- Gile, L.H., Ahrens, R.J., Anderson, S.P. (Eds.), 2003. Supplement to the Desert Project Soil Monograph: Soils and Landscapes of a Desert Region Astride the Rio Grande Valley near Las Cruces, New Mexico, USDA-Natural Resource Conservation Service, Soil Survey Investigations Report No. 44, vol. 3. National Soil Survey Center, Lincoln, NE.
- Heath, R.C., 1982. Classification of ground-water systems of the United States. *Ground Water* 20 (4), 393–401.
- Heath, R.C., 1984. Ground-water regions of the United States. US Geological Survey Water-Supply Paper, vol. 2242. US Gov. Printing Office, Washington, DC.
- Heath, R.C., 1987. Basic groundwater hydrology. U. S. Geol. Surv. Water-Supply Pap. 2220 84 pp.
- Hillel, D., 1982. *Introduction to Soil Physics*. Academic Press, Orlando, FL.
- Hopkins, D.G., 1997. Hydrologic and abiotic constraints on soil genesis and natural vegetation patterns in the sandhills of North Dakota. Ph.D. Dissertation, Soil Science Department, North Dakota State University, Fargo, ND.
- Hudnall, W.H., Szogi, A., Touchet, B.A., Daigle, J., Edwards, J.P., Lynn, W.C., 1990. VIII International soil correlation meeting on classification and management of wet soils. Guidebook for Louisiana. USDA, Soil Conservation Service, Lincoln, NE.
- Iskandar, I.K., Wright, E.A., Radke, J.K., Sharratt, B.S., Groenevelt, P.H., Hinzman, L.D. (Eds.), 1997. Proceedings of the International Symposium on Physics, Chemistry, and Ecology of Seasonally Affected Soils, Fairbanks, Alaska—June 10–12, 1997. US Army Cold Regions Research and Engineering Laboratory, Special Report 97-10, National Technical Information Service, Springfield, VA.
- Jenkinson, B.J., Franzmeier, D.P., Lynn, W.C., 2002. Soil hydrology on an end moraine and a dissected till plain in west-central Indiana. *Soil Sci. Soc. Am. J.* 66, 1367–1376.
- Johnston, C.A., 2001. Wetland soil and landscape alteration by beavers. In: Richardson, J.L., Vepraskas, M.J. (Eds.). *Wetland soils: genesis, hydrology, and classification*. Lewis Publishers, CRC Press LLC, Washington, DC. ISBN 1-56670-484-7.
- Karathanasis, A.D., Thompson, Y.L., Barton, C.D., 2003. Long-term evaluations of seasonally saturated wetlands in western Kentucky. *Soil Sci. Soc. Am. J.* 67, 662–673.
- Kimble, J.M., Ahrens, R.J. (Eds.), 1994. Proceedings of the Meeting on the Classification and Management of Permafrost Affected Soils—July, 1993, USDA-Soil Conservation Service. National Soil Survey Center, Lincoln, NE.
- Lowrance, R., Altier, L.S., Newbold, J.D., Schnabel, R.R., Groffman, P.M., Denver, J.M., Correll, D.L., Gilliam, J.W., Robinson, J.L., Brinsfield, R.B., Staver, K.W., Lucas, W., Todd, A.H., 1997. Water quality functions of riparian forest buffers in Chesapeake Bay Watersheds. *Environ. Manage.* 21 (5), 687–712.
- Mando, A., Stroosnijder, L., Brussard, L., 1996. Effects of termites on infiltration into crusted soil. *Geoderma* 74, 107–113.
- McDaniel, P.A., Buol, S.W., 1991. Manganese distribution in acid soils of the North Carolina Piedmont. *Soil Sci. Soc. Am. J.* 55, 152–158.
- McDaniel, P.A., Bathke, G.R., Buol, S.W., Cassel, D.K., Falen, A.L., 1992. Secondary manganese/iron ratios as pedochemical indicators of field-scale throughflow water movement. *Soil Sci. Soc. Am. J.* 56, 1211–1217.
- Park, S.J., Burt, T.P., 1999. Identification of throughflow using the distribution of secondary iron oxides in soils. *Geoderma* 93, 61–84.
- Parlange, M.B., Hopmans, J.W. (Eds.), 1999. *Vadose Zone Hydrology: Cutting Across Disciplines*. Oxford University Press, New York, NY.
- Pennock, D.L., Zebarth, B.J., de Long, E., 1987. Landform classification and soil distribution in hummocky terrain, Saskatchewan, Canada. *Geoderma* 40, 297–315.
- Rabenhorst, M.C., Bell, J.C., McDaniel, P.A. (Eds.), 1998. *Quantifying Soil Hydromorphology*, Soil Science Society America Special Publication, vol. 54, Madison, WI.
- Richardson, J.L., 1993. Personal communication.
- Richardson, J.L., Brinson, M.M. 2001. Wetland soils and hydrogeomorphic classification of wetlands. In: Richardson, J.L., and Vepraskas, M.J. (Eds.). *Wetland soils: genesis, hydrology, and classification*. Lewis Publishers, CRC Press LLC, Washington, DC. ISBN 1-56670-484-7.
- Richardson, J.L., Vepraskas, M.J. (Eds.), 2001. *Wetland soils: genesis, hydrology, and classification*. Lewis Publishers, CRC Press LLC, Washington, DC. ISBN 1-56670-484-7.
- Rosenshein, J.S., 1988. Chapter 21: region 18—alluvial valleys (pp. 165–175). In: Black, W., Rosehshein, J.S., Seaber, P.R. (Eds.), *Hydrogeology, Decade of North America Geology Series*, vol. O-2. Geological Society America, Boulder, CO, ISBN: 0-8137-5206-X.
- Rosenzweig, C. (Ed.), 2001. Impacts of El Nino and climatic variability on agriculture, ASA Special Publication, vol. 63. American Society Agronomy, Madison, WI, ISBN: 0-89118-148-2.
- Schoeneberger, P.J., Amoozegar, A., Buol, S.W., 1995. Physical property variation of a soil and saprolite continuum at three geomorphic positions. *Soil Sci. Soc. Am. J.* 59, 1389–1397.
- Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Broderson, W.D. 2002. Field book for describing and sampling soils, version 2.0. USDA-NRCS, US Government Printing Office, Washington, DC.
- Shaw, J.N., Bosch, D.D., West, L.T., Truman, C.C., Radcliffe, D.E., 2001. Lateral flow in loamy to sandy Kandiodults of the Upper Coastal Plain of Georgia (USA). *Geoderma* 99, 1–25.
- Soil Conservation Service, 1981. Land resource regions and major land resource areas of the United States. USDA Agriculture

- Handbook, vol. 296. US Government Printing Office, Washington, DC.
- Soil Survey Staff, 1993. Soil survey manual. USDA Agriculture Handbook 18. US Government Printing Office, Washington, DC.
- Steinwand, A.L., Richardson, J.L., 1989. Gypsum occurrence in soils on the margin of semi-permanent Prairie Pothole Wetlands. *Soil Sci. Soc. Am. J.* 53, 836–842.
- Thompson, J.A., Bell, J.C., 1998. Hydric conditions and hydro-morphic properties within a Mollisol catena in southeastern Minnesota. *Soil Sci. Soc. Am. J.* 62, 1116–1125.
- Thompson, J.A., Bell, J.C., Butler, C.A., 2001. Digital elevation model resolution: effects on terrain attribute calculation and quantitative soil-landscape modeling. *Geoderma* 100, 67–89.
- Wakeley, J.S., Sprecher, S.W., Lynn, W.C. (Eds.), 1996. Preliminary investigations of hydric soil hydrology and morphology in the United States. US Army Corps of Engineers, Wetlands Research Program Technical Report WRP-DE-13, Washington, DC.
- Wilson, G.V., Jardine, P.M., Luxmoore, R.J., Jones, J.R., 1990. Hydrology of a forested hillslope during storm events. *Geoderma* 46, 119–138.
- Winter, T.C., Woo, M.K., 1990. Hydrology of lakes and wetlands (pp. 159–187). In: Wolman, M.G., Riggs, H.C. (Eds.), *Surface Water Hydrology, Decade of North American Geology*, vol. 0–1. Geological Society of America, Boulder, CO.
- Wysocki, D.A., Schoeneberger, P.J., 2000. Geomorphology of soil landscapes. In: Sumner, M.E. (Ed.), *Handbook of Soil Science*. CRC Press LLC, Boca Raton, FL, ISBN: 0-8493-3136-6.